Winter Temperature Variability During Warming and Cooling Periods in the Conterminous United States, 1947-1992

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Summary:
Much literature has reported on the concept of increased surface temperature variability during cool periods, although analyses on temperature records have rendered inconsistent results. In addition, temperature variability during transition periods has been rarely investigated. This study examines temperature variability during wintertime cooling (1947-1977) and warming (1978-1992) periods for the conterminous United States to determine both whether temperature variability is different during warming or cooling periods, and whether the change in variability is supported by midtropospheric circulation conditions. Our results indicate that regions with high temperature variability are mostly found below the troughs in the midtropospheric pressure fields. The direction of change in temperature variability corresponding to cooling or warming conditions, however, varied spatially. For the south-eastern and northeastern United States, winter temperatures were more variable during the cooling period than during the warming period, while the northern and central Great Plains had greater temperature variability during the warming period than the cooling period. Similar spatial patterns are also found for the changes in the variability of geopotential height fields. Such spatial patterns in the temperature and height variability during warming and cooling periods may be related to the dominant midtropospheric circulation patterns, such as the different phases of the Pacific-North American teleconnection pattern, and the El Niño/Southern Oscillation events. It is concluded that the response of interannual temperature variability to climatic changes is determined by the variation in circulation patterns, and therefore, not spatially uniform.

Article:

1. Introduction

An axiom regarding climatic fluctuations is that cold periods are characterized by increased temperature variability (Tyson, 1977). Studies that support this concept have been presented over a variety of temporal scales. Lamb (1982) for example, summarized the results of several studies from Europe that were based on historical weather documents and concluded that there was increased temperature variability during the Little Ice Age of 1400-1850. Similarly, analyses of past climates by Bryson and Murray (1977) and Tyson (1977) have indicated that greater temperature variability has occurred in concert with cooler periods. During the 20th century, both Lamb (1982) and Bryson and Murray (1977) have suggested that there was again increased temperature variability in the Northern Hemisphere associated with cooling temperatures that began in the late 1940s and continued through the mid-1970s when their analyses ended. More recently, however, Karl et al. (1995) reported that temperature variability has decreased in many parts of the world, possibly associated with global warming.

Several studies have attempted to validate the concept of cooler temperature/more variability in North America. Van Loon and Williams (1978) compared mean temperature and the variability of temperature during two periods, 1876-1926 and 1925-1975, for 21 cities in North America and concluded that their data did not support the association between cold periods and increased temperature variability. Similarly, Diaz and Quayle (1980) examined relationships between changes in mean temperature and variability for the United States during three periods based on temperature: 1895/96-1919/20 (cooler), 1920/21-1953/54 (warmer), and 1954/55-1976-77 (cooler). For winter temperatures, they found that the cooler/more variable, warmer/less variable relationship only existed in the southeast.

Numerous studies have suggested strong associations between mid-troposphere pressure field and surface temperature (e.g., Erickson, 1984; Klein and Kline, 1984; Shabbar et al., 1990; Skeeter, 1990). It has been suggested that the alternation of zonal and meridional midtroposphere flow patterns across the northeast Pacific and North America is probably the most influential factor on the spatial pattern of interannual surface temperature variability in the United States (Yarnal and Leathers, 1988; Leathers et al., 1991; Leathers and Palecki, 1992). Such variation of the upper-air flow patterns is represented by the Pacific/North American (PNA) teleconnection. During the classic PNA phase, the meridional flow pattern dominates midtropospheric circulation over the northeast Pacific and North America, expressed as deepened troughs over the southeastern United States and northeast Pacific, and an enhanced ridge over the Rockies in the 500 hPa and 700 hPa geopotential heights. During the reversed PNA (RPNA) phase, the zonal flow pattern dominates, characterized by flattened troughs and a lowered ridge at the above locations.

Although the connections have been suggested, to our knowledge few studies have been conducted to associate surface temperature variability with the analysis of geopotential height data. We also feel that it is important to investigate temperature variability during transition periods, either from a warmer condition to a cooler condition or vice versa. It is widely accepted that long-term global warming has occurred since the mid-19th century (Jones, 1994). If this trend has resulted from the increased atmospheric green-house gases, it should continue into the foreseeable future. To understand how interannual temperature variability will change under such a condition now has both theoretical and practical implications. However, it is difficult to compare temperature variability during this period with any earlier cooling periods largely because of the lack of observed data. It is even more difficult to study the spatial pattern of the changes in the characteristics of temperature variability as stations with long and reliable records are distributed unevenly. One likely solution to circumvent these difficulties is to identify shorter periods with consistent trends in temperature, then investigate the characteristics of temperature variability during such periods.

The purpose of this study is to examine surface temperature variability in the United States during wintertime warming and cooling periods from 1947-1992 and to determine whether there is a link between surface temperature variability and midtropospheric circulation patterns. Unlike the relationship between daily and diurnal temperature variability and climatic changes, the variation of interannual variability in relation to climatic changes is poorly understood. Some studies have shown that interannual variability has decreased with the warming temperatures (Karl et al., 1995), while others have insisted that it has increased in recent years (Parker et al., 1994). Specifically, we will examine whether any spatial patterns exist in the changes of winter temperature variability in relation to temperature trends. Then we will attempt to explain such patterns using upper-air circulation patterns.

2. Data

The 500hPa and 700hPa geopotential height data were obtained from the National Center for Atmospheric Research (NCAR) as a subset of the National Meteorological Center data set. The geopotential heights are spatially represented by grid points separated by 5° of latitude, and longitude, and range from 20°N to 60°N and from 70°W to 125°W. The 700hPa height data were observed twice daily at 03 and 15 UTC prior to June 1957. During the 1957 International Geophysical Year, the observation time was changed to 00 and 12 UTC. We averaged the twice daily data to get monthly means for the 3 winter months (DJF) and then calculated the seasonal means during the study period. The 500 hPa heights, however, were only available at 15 UTC during January 1946 to March 1955. To keep the data series as long as possible and minimize the errors associated with observation time change (Lambert, 1990), we used the data recorded at 15 UTC prior to June 1957 and those at 12 UTC afterwards.

Our original temperature database consists of monthly and seasonal values for the 1221 stations of the U.S. Historical Climatology Network (HCN) from the late 1800s through 1992. This dataset is widely considered the best source of data available for the conterminous United States (Karl et al., 1990). All stations have been corrected for potential sources of errors including time of observation bias, instrument changes, station relocations and urbanization effects (Karl et al., 1986; Karl and Williams, 1987; Karl et al., 1988). For our study, we reduced the number of stations by selecting only those stations whose decile consistency ranking was from 0 (highest consistency) to 3. Data consistency is evaluated by comparing the temperature record at a given station with those for its surrounding stations (Karl et al., 1990). This process assured us of choosing the 440 most consistent stations available.

3. Methods

3.1 Principal Component Analysis

To determine spatial patterns of temperature variability, we used principal component analysis (PCA) to identify regions in the U.S. based on their temperature variation characteristics. To reduce errors associated with uneven distributions of stations, 53 stations closest to the 5° × 5° grid points were selected. We then performed principal components analysis on temperature records of the 53 stations. Based on minimum eigenvalues of 1.0 or greater and an assessment of the scree plot of explained variance against the number of principal components (Zar, 1984; SAS, 1990), six principal components (PCs) were retained, and then rotated by an orthogonal method (VARIMAX). The rotated PCs usually represents better-defined geographic regions with distinct variation regimes than the unrotated PCs (White et al., 1991). Figure 1 shows that the loadings, or the correlation coefficients between the 6 rotated principal components and the original temperature anomalies, represented distinct geographical regions. In each region, winter temperatures at the 30 stations closest to the center were used to calculate regional means. In addition, we found one area not well represented by any of the six PCs, so we designated it as region 7.

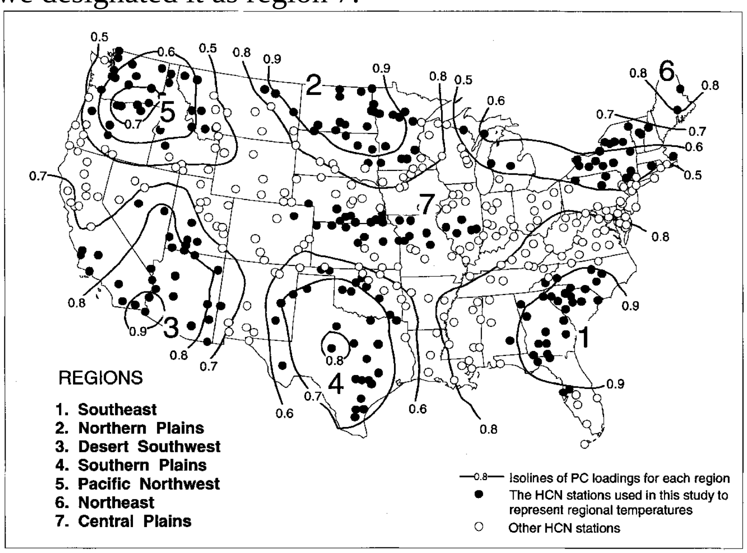

Fig. 1. Location of 440 Historical Climatology Network stations used in this study and the regions defined by principal component analysis

3.2 Cooling and Warming Periods

To determine the cooling and warming periods for the entire conterminous U.S., we calculated the mean winter temperature as the average of all 7 regions. Although the stations tend to cluster at the center of the 7 regions, the resulted mean time-series should still be very representative since a total of 210 stations were used across the entire U.S. Then the U.S. winter temperature time-series was smoothed by a low-pass 11-year filter (Mitchell et al., 1966) to reveal trends. We also fit a third-order polynomial curve to the time-series. Points of inflection along the polynomial curve were used as a reference to divide cooling and warming periods. Finally, we examined trends in the scores of the first two unrotated PCs that represent more than 65% of total variance in the temperature field. Based on these methods we identified a general cooling period and a general warming period.

3.3 Interannual Temperature Variability

We calculated the standard deviations and variances during each period for the regional winter temperature time-series to represent interannual variability. The variances were com-pared by a *F*-test for statistical significance, in which the null hypothesis was equal variances during the two periods (SAS, 1990). We also calculated the first-order absolute difference ($|dT|$) as

$$|dT_t| = |T_t - T_{t-1}|,$$

where T_t is the winter temperature of any year t and T_{t-1} is the temperature of the previous year. This is a measure of high-frequency interannual variability (Karl et al., 1985). Then the mean first-order differences during the two periods were compared by an independent Student's **t** test (Zar, 1984; SAS, 1990). As the regional temperature time-series have aggregated individual station time-series and, therefore, may have changed the characteristics of variability, we also calculated standard deviations for the 30 stations in each region during the cooling and warming periods. For each region, the standard deviations of the 30 stations during the two periods were compared by a matched-pair Student's **t** test to show how consistent were the changes in temperature variability in each region.

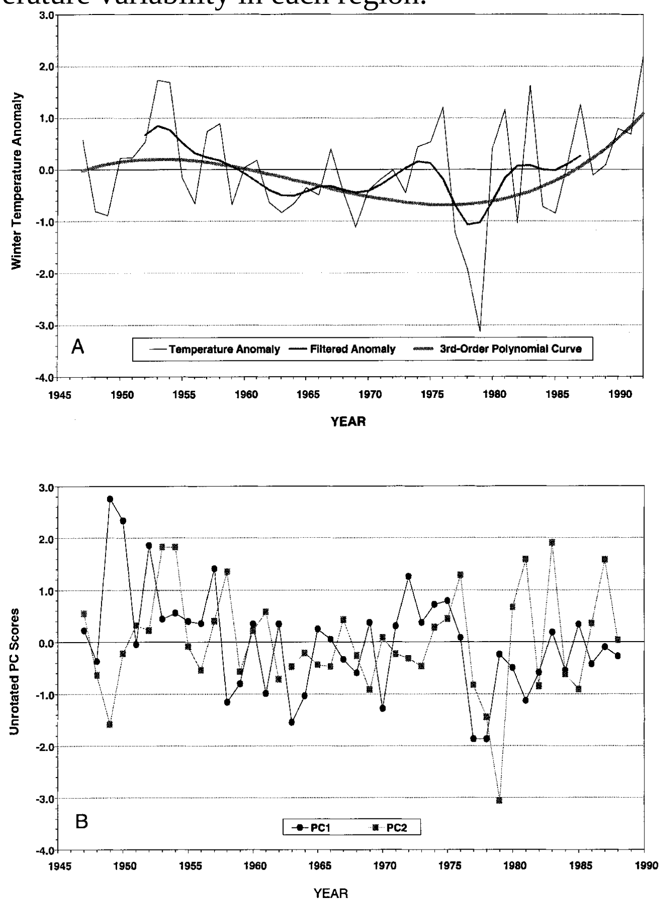

Fig. 2. Trends in the U.S. mean winter temperature anomalies calculated as the mean of the seven regional time-series (A), and the first two unrotated PC scores based on the result of principal component analysis of temperature anomalies at 53 stations (B)

In this study an attempt was made to relate surface temperature variability to the variability in the midtropospheric geopotential height fields. Correlations between regional temperature and geopotential heights were first performed to specify the spatial association between the surface and midtropospheric conditions. Then the difference in variability of surface temperature and geopotential height were compared between the cooling and warming periods. For the purpose of mutual verification, the height data for both levels were used in this study. To explain the changes in the variability of surface temperature and midtropospheric geopotential height, we examined variations in the midtropospheric circulation patterns during the study period. Trend slopes of geopotential heights during the cooling and warming periods were determined by simple bivariate regression analysis for each grid using time as the independent variable. In addition, circulation pattern was represented by the PNA index as described in Horel and Wallace (1981). This index is expressed as a linear function of normalized 700 hPa geopotential height anomalies (z), using the 1951-1980 means and standard deviations, over the northeast Pacific (45°N, 165°W), southwestern Canada (the Canadian Rockies at 55°N, 115°W), and the southeastern United States (30°N, 85°W):

PNAI = z(55°N, 115°W)
- 1/2[z(45°N, 165°W)
+ z(30° N, 85° W)].

Positive index values indicate the classic PNA teleconnection pattern with meridional midtropospheric flows across the United States, while negative values indicate the reverse PNA (RPNA) pattern with zonal flows.

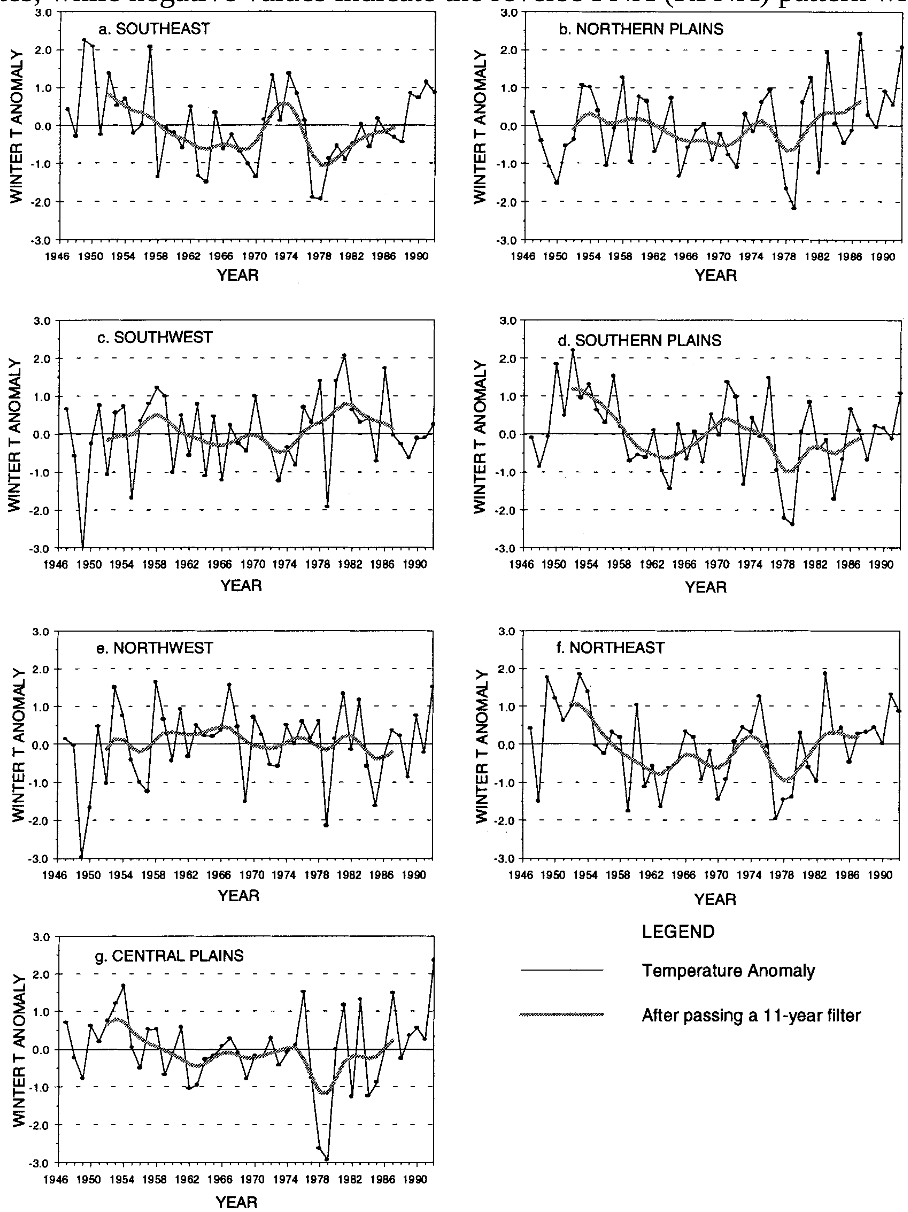

Fig. 3. Mean winter temperature anomalies for each of the seven regions

4. Results and Discussion

4.1 Temperature Trends

The U.S. winter temperature time-series based on data for 210 stations shows a general cooling trend from the early 1950s to the 1970s and a warming trend from the late 1970s to the 1990s (Fig. 2). Such a variation pattern is in general comparable to the temperature trends in the Northern Hemisphere (Jones, 1994). A general cooling trend was found in the North Hemisphere land surface temperature record from the 1930s. A short warming occurred in the early 1950s, but the general cooling trend continued into the 1970s, which was followed by a warming trend. In our record, the lowest winter temperature occurred in 1979, while the lowest point in the smoothed series was found in 1978. The polynomial curve indicates a cooling trend prior to the inflection point around 1976-77, and a warming trend afterward. The scores of the first two unrotated PCs show similar patterns: the first PC has the lowest score values in 1977 and 1978, while the second PC has the lowest score in 1979 (Fig. 2). As a compromise among the above methods, we defined the cooling period for the conterminous

United States from 1947 to 1977 and the warming period from 1978 to 1992. The regional temperature time series 1947-1992 show similar early cooling and later warming trends for the Southeast, Northern Plains, Central Plains, Southern Plains, and the Northeast (Fig. 3). Less defined trends exist for the Desert Southwest and Pacific Northwest regions.

Table 1. *Standard Deviations of the Regional Winter Temperature During 1947–77 and 1978–92 Periods and the Result of F Test on the Variances During the two Periods*

Region	Standard Deviations 1947–77	1978–92	Change	F	α
Southeast	1.81	1.37	−0.44	1.74	0.2748
Northern Plains	1.94	3.35	+1.41	2.98	0.0117
Desert Southwest	1.10	1.19	+0.09	1.17	0.6923
Southern Plains	1.20	1.31	+0.11	1.20	0.6565
Pacific Northwest	1.68	1.74	+0.06	1.08	0.8234
Northeast	1.48	1.32	−0.16	1.27	0.6536
Central Plains	1.11	2.42	+1.31	4.73	0.0004
Entire U.S.	0.78	1.44	+0.66	3.38	0.0050

4.2 Interannual Variability during the Cooling and Warming Periods

During the later warming period, temperature standard deviations were lower in the Southeast and Northeast compared with the earlier cooling period, but higher in all the other regions, including the conterminous United States (Table 1). The *F*-test indicated that in the Northern Plains and Central Plains the temperature variances were significantly higher during the warming period than during the cooling period. Additionally, the warming-period temperature variability for the entire United States was significantly higher than the cooling-period variability. When examining the absolute first-order differences presenting high-frequency interannual variability, similar patterns were revealed (Table 2). The increase in variability was statistically significant for the Central Plains and the United States as a whole, while the significance level is 0.059 for the North Plains. Furthermore, the warming-period variability was significantly lower than the cooling-period variability in the Southeast. Minor discrepancies were noticed for the Desert Southwest, Southern Plains, and Northeast, but the changes were small and insignificant in both methods.

Table 2. *Independent Student's* **t** *Test on Mean First-order Differences of the Regional Winter Temperature During 1947–77 and 1978–92*

Region	Mean Differences 1947–77	1978–92	Change	t	α
Southeast	1.82	0.76	−1.06	3.58	0.0009
Northern Plains	2.17	3.58	+1.41	2.01	0.0588
Desert Southwest	1.39	1.29	+0.10	0.31	0.7558
Southern Plains	1.32	1.16	−0.16	0.65	0.5171
Pacific Northwest	1.82	2.21	+0.39	0.96	0.3445
Northeast	1.44	1.14	−0.30	0.83	0.4108
Central Plains	1.12	2.25	+1.13	2.83	0.0109
Entire U.S.	0.69	1.34	+0.65	2.27	0.0349

Matched-pair *Student's* **t** test on mean standard deviations of the 30 stations in each region revealed that the changes in the interannual temperature variability between the cooling and warming periods were significantly consistent for five out of the seven regions (Table 3). Only the Southern Plains and Pacific Northwest did not have consistent changes in the standard deviations. The Southeast and Northeast had consistent decreases in standard deviations, indicating that during the warming period interannual temperature variability was lower than during the cooling period for the majority of the thirty stations in each region. In contrast, the Northern Plains, Desert Southwest, and Central Plains had consistent increases, indicating that temperature variability was higher during the warming period than during the cooling period for the majority of the stations. The most prominent increase in temperature variability was found in the Northern and Central Plains (Table 3). It is noteworthy that although the increase in temperature variability is small in the Desert Southwest, the change is consistent among the 30 stations.

More detailed spatial patterns of temperature variability were displayed by mapping the percentage of change in temperature standard deviations at all 440 HCN stations during the cooling and warming periods (Fig. 4). Compared with the earlier cooling period 1947-1977 (Fig. 4A), the decreases in temperature variability were found in the east from the Great Lakes region eastward, and in the west in northern California (Fig. 4B). The greatest reduction is found in the deep south and southeast. In contrast, temperature variability increased as much as 120 percent in the Midwest, showing that winters in the Great Plains during the warming period have been characterized by much greater interannual variability. Areas of little or no change are found in the Pacific northwest and southern California. The apparent conflicting results for the Southern Plains (Table 3 and Fig. 4B) are because of the aggregation of stations in southern Texas that have reduced temperature variability and those in northern Texas and Oklahoma that have increased temperature variability.

Table 3. *Matched-pair Student's* **t** *Test on Mean Standard Deviations of Regional Winter Temperature During 1947–1977 and 1978–1992*

Region	N	Mean Difference (°C)	*T*	α
Southeast	30	−0.51	−13.13	0.0001
Northern Plains	30	1.31	21.67	0.0001
Desert Southwest	30	0.08	2.50	0.0181
Southern Plains	30	0.10	1.03	0.3111
Pacific Northwest	30	0.02	0.48	0.6373
Northeast	30	−0.12	−2.31	0.0283
Central Plains	30	1.13	19.15	0.0001

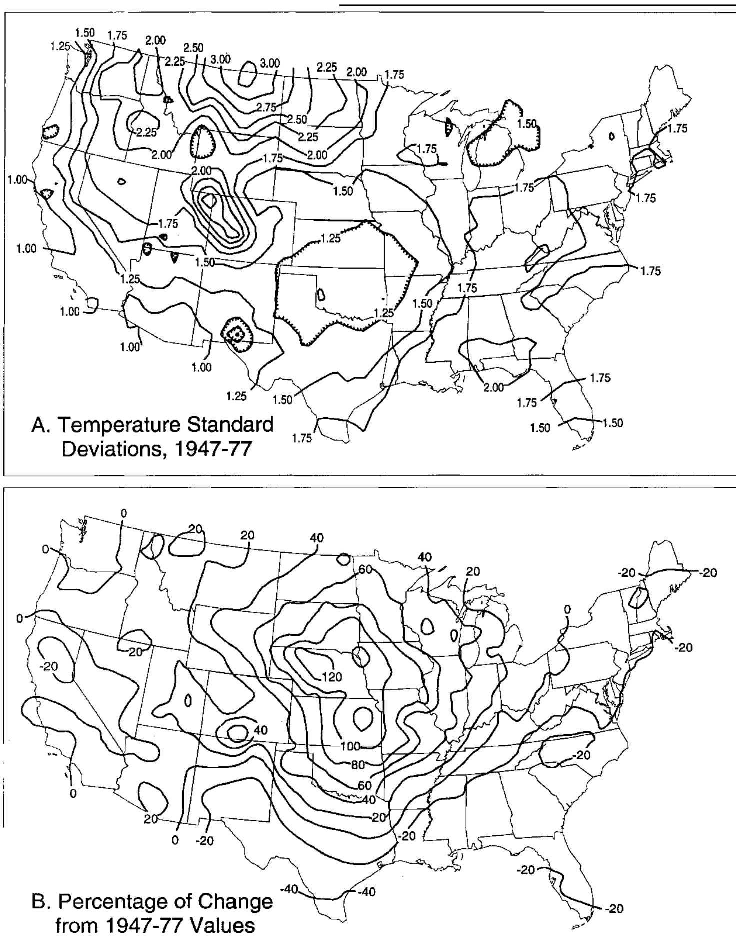

Fig. 4. Changes in the standard deviation of winter temperature for all 440 stations. A) Standard deviations during 1947–1977; B) Percentage of change in standard deviation during 1978–1992 from the earlier period

4.3 Variability in Midtropospheric Geopotential Heights

To ensure definitive spatial associations between regional temperature and midtropospheric geo-potential heights at certain grid points, regional temperatures were correlated with geopotential heights throughout the study area. The highest isolines of correlation coefficients were then mapped for each region (Fig. 5). Surface temperature appears to be best correlated with the heights in the general vicinity, although not exactly above the surface regions. These patterns generally conform with Klein and Kline (1984). High correlations between surface temperatures and geopotential heights suggest that the temperature variability may be related to the variability of pressure height field.

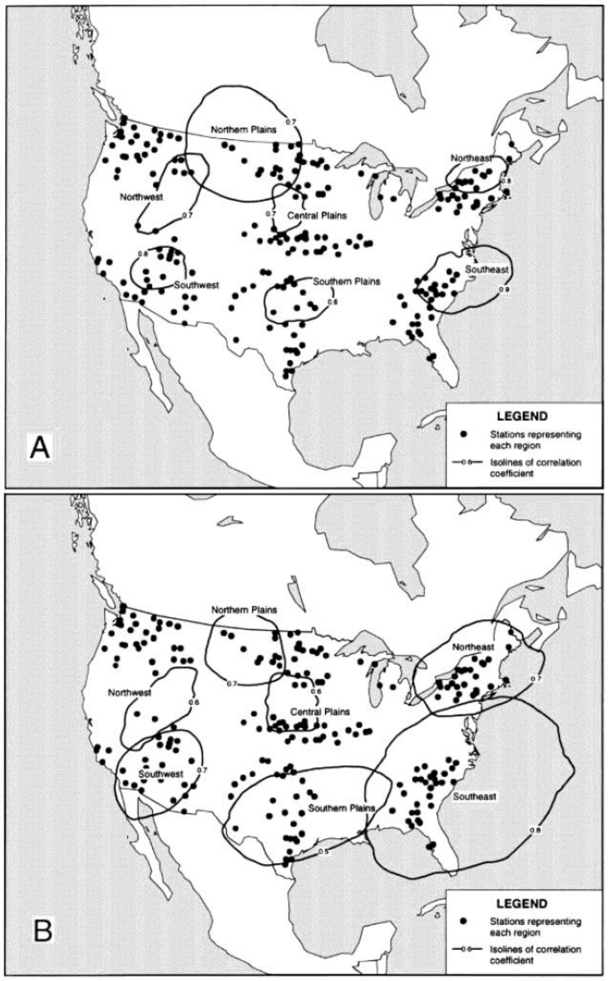

Fig. 5. Correlation coefficients between surface regional temperature and geopotential heights for all seven study regions. A 500 hPa; B 700 hPa

The percentage of change in the standard deviation of both 700 hPa and 500 hPa heights between the cooling and warming periods show distinct spatial patterns (Fig. 6). For the 500hPa heights, two areas experienced a decrease in the variability of heights during the warming period (Fig. 6A). In the east, this pattern extends from approximately 90° W eastward. A decrease is also exhibited in the far west, particularly from 115° W westward and north of 34° N. One area of increased variability was found in the central U.S., centered at approximately 45° N and 100°W. Similar patterns exist for the 700hPa heights (Fig. 6B). The percentage of changes in standard deviation of heights for the central U.S., however, is smaller than for the 500 hPa heights.

Since regions of increased or decreased surface temperature variability coincide with locations with similar changes in geopotential heights, it is reasonable to suggest that surface temperature variability varies with upper-air pressure height variability.

4.4 Changes in the Midtropospheric Flow Patterns

The changes in variability of surface temperature and geopotential heights may be related to certain changes in the midtropospheric flow pattern. We found distinct spatial patterns in the trend slopes of the 500hPa and 700hPa heights for the cooling and warming periods (Fig. 7). The trend slopes for the 500hPa heights during the cooling period (1947-1977) show a decrease occurring from approximately 105°W eastward with the largest decreases in the Southeast and Northeast (Fig. 7A). West of 105°W, in the meanwhile, trend slopes increased with the steepest slope occurring in the Pacific Northwest. During the warming period (1978-1992), geo-potential heights were generally rising, except for the Desert Southwest that had a decline trend (Fig. 7B). The steepest positive slopes were in the Southeast and Pacific Northwest, while the trend slopes were lower in the Northern and Central Plains. Similar patterns exist for the 700 hPa heights, but the trend slopes were not as prominent as for the 500 hPa heights (Fig. 8).

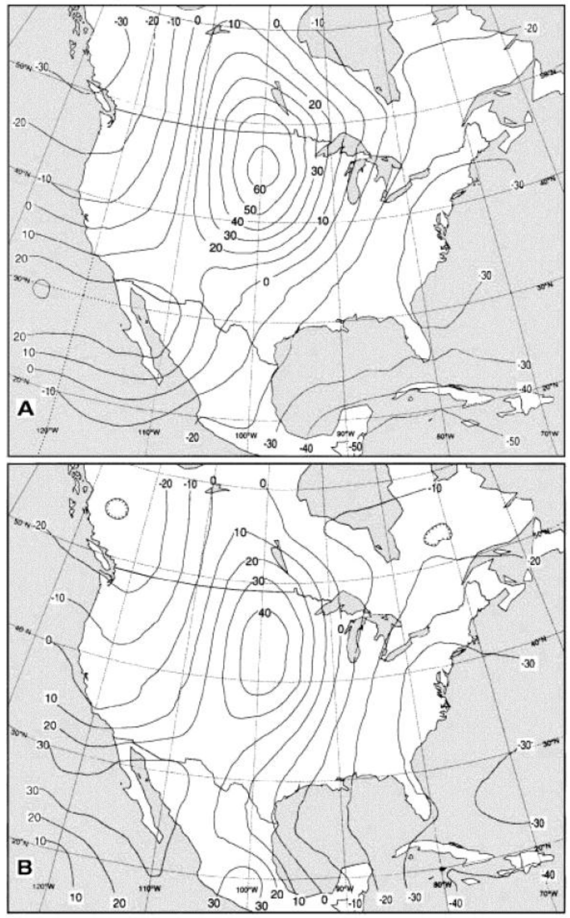

Fig. 6. Percentage of change in standard deviation of winter geopotential heights: 1947–1977 versus 1978–1992. A) 500 hPa; B) 700 hPa

In summary, the longwave trough over the eastern United States became increasingly deepened, while the longwave ridge over the western U.S. was somewhat enhanced during the cooling period. Such changes clearly indicate gradually enhanced strength of the PNA teleconnection pattern with a more meridional midtropospheric flow pattern across the U.S. (Yarnal and Leathers, 1988; Shabbar et al., 1990; Leathers et al., 1991; Davis and Benkovic, 1992, 1994). During the warming period, however, there seemed to be a shift of the longwave trough axis from the east towards the west-central U.S. where the magnitude of increase in geopotential heights is lower than those over the Pacific Northwest and South-east, and the heights actually decreased over the Desert Southwest. In addition, as the magnitude of geopotential height rising was most significant in the eastern U.S., the amplitude of the long-waves must have been flattened because of the filled trough. These changes in the geopotential height field are also indicated by the winter PNA index. The quasi-periodic oscillation pattern can be seen clearly in Fig. 9, which is mainly responsible for interannual temperature variability in the eastern United States (Leathers and Palecki, 1992). More important, however, is the trend of peak index values that represent the strength of the PNA teleconnection pattern. Previous studies have suggested increased strength of the PNA pattern from the early 1950s to the 1980s (e.g., Yarnal and Leathers, 1988; Leathers and Palecki, 1992). With a longer record, however, we could argue that the peaks of the PNA index reached the highest value around 1977-1978 and have decreased gradually since then. Additionally, the interannual variability of the index values was higher during the early cooling period (s.d. = 1.980) than during the warming period (s.d. = 1.504).

4.5 Temperature Variability During the Cooling Period

The causative mechanism behind cooling/more variable conditions is based on the assumption of an amplification of the longwave pattern (increased meridional pattern) in the westerlies (Bryson and Murray, 1977; Tyson, 1977; Lamb, 1982). Namias (1970) argued that above-normal SSTs of the North Pacific help from the elevated upper-air-ridge. Subsequently, cyclonic storms, with a warmer initiation, become more intense and further amplify the longwave pattern down-stream of the ridge. Increased meridional circulation will in turn both increase the redistribution of sensible heat flow in the midlatitudes and the frequency of blocking anticyclones and cut-off lows. These conditions would reduce the movement of migrating waves (shortwaves), thus creating an environment that increases anomalous temperature conditions initially caused by amplified longwave patterns (Harman, 1991).

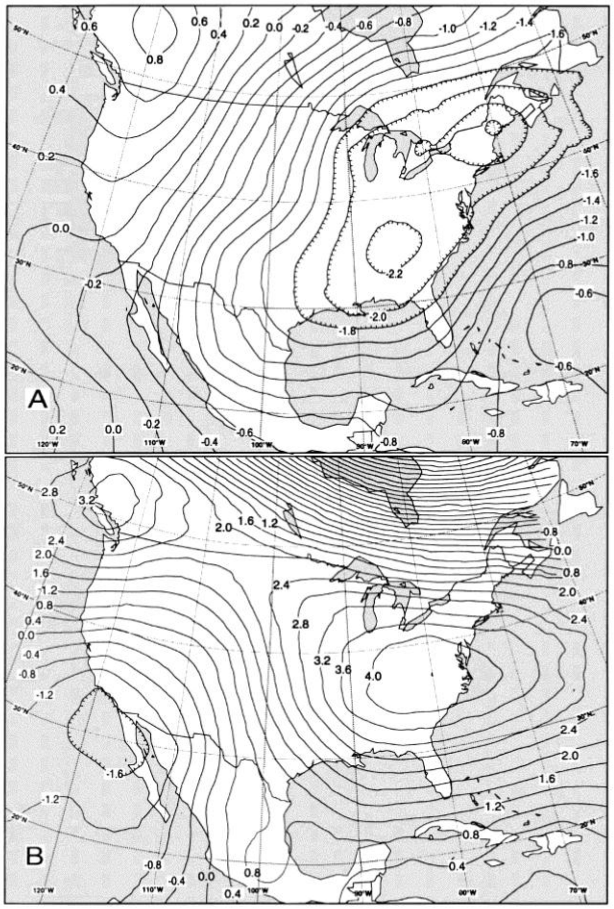

Fig. 7. Trend slopes (meters/year) of the 500 hPa heights during the cooling and warming periods, calculated by linear regression with heights at a given grid as the dependent variable and time as the independent variable. A) 1947–1977; B) 1978–1992

Once established several feedback mechanisms exist to enhance or prolong the amplified wave pattern (Dickson and Namias, 1976) that creates the more variable conditions. Positive feedbacks between temperature and snow cover may also increase interannual temperature variability. During periods of extensive snow cover in the central and eastern United States, there is a more southerly migration of the storm tracks that enhances baroclinicity, increases cyclonic activity, and reinforces anomalous circulation patterns (Namias, 1962, 1985). Also the snow cover prevents the Polar or Arctic air masses from being modified before they reach the southern part of the United States. If the initial amplification of longwaves does not occur, then these positive feedbacks would fail to sustain a strong PNA pattern. In such a case, a weak PNA pattern or even a reversed PNA pattern may dominate that winter. Therefore, during the cooling period the eastern United States, especially the South-east, was located at the axis of the longwave trough and experienced the greatest temperature variability as the position of the Polar Front jet oscillated northward and southward with the midtropospheric flow patterns alternating be-tween strong PNA and weak reversed PNA phases (Fig. 10). As the trough axis shifted eastward or westward, a significant portion of the region will be affected by the Polar or Arctic air masses or by the tropical maritime air masses alternatively. Deep cyclonic storms accompanied by Polar and Arctic air masses moved across much of the southeast from time to time during the years dominated by the PNA phases (van Loon and Williams, 1977; Zishka and Smith, 1980). Concurrently, the Central and Northern Plains were located in the rear portion (western edge) of the trough, constantly under the northwesterly upper-air flow and polar/arctic air masses. The winter temperature should be increasingly colder than normal, but with relatively low variability.

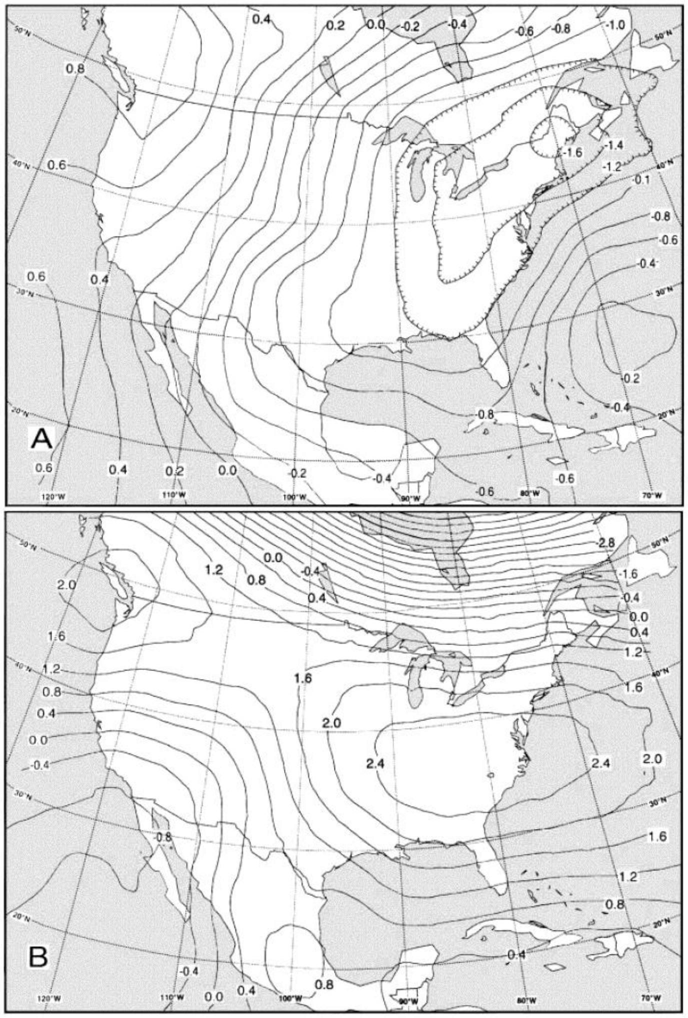

Fig. 8. As in Fig. 7, except for 700 hPa heights

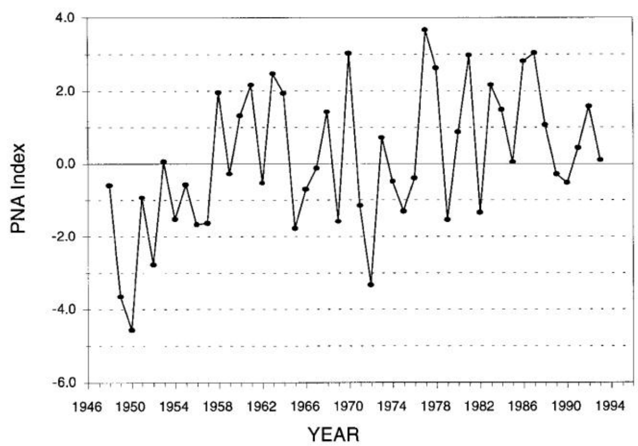

Fig. 9. Winter PNA index values during 1947–1992

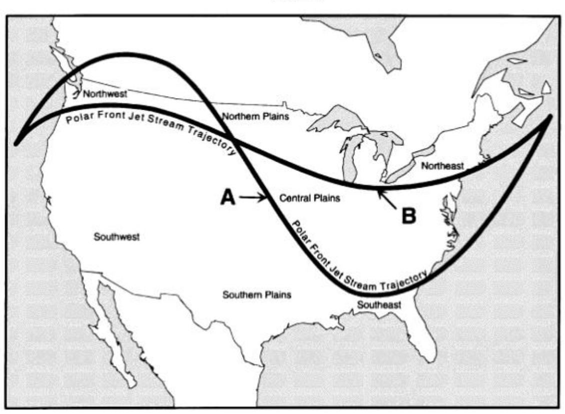

Fig. 10. Positions of polar front jetstream trajectories during the cooling periods dominated by strong PNA (labeled as A) and weak reversed PNA (B) phases. (Adapted from Leathers et al., 1991)

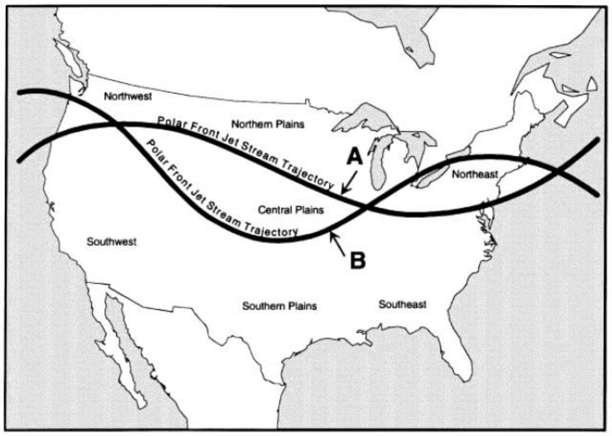

Fig. 11. Positions of polar front jetstream trajectories during the warming period with two possible scenarios. One is a flattened longwave pattern (zonal or reversed PNA pattern, labeled as A); while the other is a shift of the trough position to the central United States (B)

4.6 Temperature Variability during the Warming Period

Our results show that during the warming period, increased variability consistently occurred in three regions, the Northern Plains, Central Plains, and Desert Southwest (Table 3). Such a relationship is substantially less documented. During the warming period, two midtropospheric flow patterns may exist. One is a flattened longwave pattern (zonal flows) with the polar-front jet stream trajectories located north of the southeastern U.S. (Fig. 11). In this case, the eastern United States is influenced mostly by relatively warm air masses from the Gulf of Mexico or Atlantic Ocean. The Central and Northern Plains may have northwesterly flow bringing relatively cold air into the region, but not as cold as in the case of an amplified longwave pattern. An alternative flow pattern occurs when the longwave trough axis is shifted to the central United States, while a ridge exists over the east (Fig. 11). The ridge may be responsible for a consistent warmer surface condition in the eastern United States, while the trough causes increased temperature variability in the central United States. Occasional intrusions of warm air masses from either the Gulf of Mexico or Pacific bring above-normal temperature to the north-central United States, creating a more variable temperature regime (Schwartz, 1991). Associated with increased frequency of midtropospheric troughs, this region has seen increased cyclonic activity (Schwartz and Skeeter, 1994), similar to the condition in the southeast during the earlier cooling period. Concurrently, the Desert Southwest is located close to the rear portion of the trough with more frequent intrusions of polar air masses, also creating a more variable temperature regime (Fig. 11). This may explain why the Desert Southwest region had a temperature decline during the general warming period. According to Fig. 7B and 8B, the second pattern (i.e., trough over the central United States) seems to be more likely than a simple flattened longwave pattern since the geopotential heights had stronger increases over both the Southeast and Pacific Northwest than over the Northern and Central Plains, while the heights over the Desert South-west actually decreased. Also, this pattern explains why temperature did not show any well-defined cooling or warming trends in the Pacific Northwest. This upper-air flow pattern also conforms with the findings by Leathers (1991) who examined relationships between midtropospheric circulation and temperature in the Great Plains. He found that in the northern Great Plains, the polar-front jet flows either north or south of the region creating larger temperature fluctuations than in the southern Great Plains.

A well-known factor of interannual temperature variability in North America is the El Niño/ Southern Oscillation (ENSO). It is widely documented that during the winter months of the warm ENSO events, the northern part of North America is characterized by above-normal temperatures and positive geopotential height anomalies; while the southeastern United States is characterized by below-normal temperatures and negative geopotential height anomalies (van Loon and Madden, 1981; Ropelewski and Halpert, 1986; Klassen et al., 1994; Bunkers et al., 1996). During the last 3 warm events of our study period (1982-83, 1986-87, and 1991-92), the Northern and Central Plains had consistent above-normal winter temperatures (Fig. 3). The ENSO events obviously increased interannual temperature variability in these two regions during the warming period. However, it is difficult to assess the impact of the ENSO events on temperature variability in other regions. Numerous studies have shown that the warm events are related to the typical PNA pattern and the meridional upper-air flow pattern across North America (e.g., Horel and Wallace, 1981; Rasmusson and Wallace, 1983; Yarnal and Diaz, 1986). However, the extratropical responses to the ENSO events are far from uniform. Keables (1992) examined the warm ENSO events during 1946-87. He found that 51% of the 36 winter months had PNA patterns, 19% had RPNA patterns, and 30% of the winters showed no PNA-related patterns. Additionally, significant departures were found among those winter months with the PNA patterns. Based on above discussion, we consider the ENSO events as an important but not the dominant factor to the spatial and temporal temperature variability across the U.S. during cooling and warming periods.

5. Conclusions

The study of temperature variability through a spatial approach during transition periods may help us understand the processes of climatic changes. Our results indicate that the cooler/ more variable relationship is valid in certain regions and can be explained by upper-air circulation patterns. We found cooling temperatures corresponding to greater variability in the Southeast and Northeast regions, while in the Northern and Central Plains, our results suggest opposite relationships, that is, interannual winter temperature variability increases during the warming period. Even the temperature record of the conterminous United States showed increased variability during the warming period. By analyzing interannual variability of midtropospheric geopotential heights during the cooling and warming periods, the relationship between surface temperature variability and upper-air height variability as established. The spatial patterns of the changes in variability indicated that temperature variability varies similarly with geopotential height variability. Compared with the early cooling period, we found generally decreased height variability over the east and increased variability over the central United States during the warming period. This is be-cause strength of the PNA teleconnection pattern was enhanced during the cooling period, indicated by both the trends in the geopotential height fields and the peak values of the PNA index. During the warming period, in contrast, strength of the PNA pattern decreased and the axis of the longwave trough probably shifted towards the north-central United States. Combined with generally warming temperatures, the midtropospheric trough caused increased cyclonic activity and occasional intrusion of relatively warm air masses. Therefore, high variability of both geopotential height and surface temperature occurred in the northern and central Great Plains.

Our results suggest that the response of regional temperature variability to climatic changes may not be spatially uniform. In any region, the relationship between temperature regime and midtropospheric circulation patterns must be investigated as the latter appear to be the mechanism behind interannual temperature variability. Our results also indicate that greatest temperature variability tends to be found at the deepened troughs of the midtropospheric pressure fields, such the southeastern United States during the cooling period, and the central United States during the warming period. Finally, the warmer/more variable relationship in the northern and central Great Plains may have resulted from the strong warm ENSO events during the later period.

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